UCID- 20062

COSMIC BOMBARDMENT

Roderick A. Hyde

March 19, 1984

Lawrence Livermore National Laboratory

This is an informal report intended primarily for internal or limited external distribution. The opinions and conclusions stated are those of the author and may or may not be those of the Laboratory.

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

CIRCULATION COPY
SUBJECT TO RECALL
IN TWO WEEKS

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government thereof, and shall not be used for advertising or product endorsement purposes.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price: Printed Copy $; Microfiche $4.50

Page Range	Domestic Price	Page Range	Domestic Price
001-025	$ 7.00	326-350	$ 26.50
026-050	8.50	351-375	28.00
051-075	10.00	376-400	29.50
076-100	11.50	401-426	31.00
101-125	13.00	427-450	32.50
126-150	14.50	451-475	34.00
151-175	16.00	476-500	35.50
176-200	17.50	501-525	37.00
201-225	19.00	526-550	38.50
226-250	20.50	551-575	40.00
251-275	22.00	576-600	41.50
276-300	23.50	601-up[1]	
301-325	25.00		

[1]Add 1.50 for each additional 25 page increment, or portion thereof from 601 pages up.

COSMIC BOMBARDMENT

Roderick A. Hyde

Physics Department, Lawrence Livermore National Laboratory, Livermore, CA 94550

Throughout its history, the Earth has been constantly bombarded by interplanetary bodies. In the maelstrom of the early Solar System, such collisions created our planet and then fed its growth. With time, the rate of such collisions has dropped enormously, as most of the loose matter has been swept either up or out of the Solar System. However, because our planet has evolved and acquired an increasingly sophisticated biosphere, the significance of cosmic bombardment has not decreased. The collision of a large asteroid or comet is widely suspected to have been responsible for climatic changes which led to the extinction of the dinosaurs and many of the Earth's other species 65 million years ago. Similiar impacts are believed to have caused other mass executions throughout our evolutionary history. The ascendency of Man and the other mammals has been made possible by this culling of their competition.

Interplanetary bombardment has thus played a brutal but highly beneficial role in the development of our planet and our species. The bombardment however, has not stopped, and we are now in the position of the dinosaurs. Fortunately, unlike our evolutionary ancestors, we have the capability to end this cannonading now, before we too are destroyed.

Collisions such as have caused previous mass extinctions are rare, occuring at 30–100 million year intervals. Hence there is a strong temptation to ignore the threat of cosmic bombardment, as presenting a very low probability danger. However, such large but rare collisions are only the most spectacular portion of the threat spectrum. The object which caused the Cretaceous extinctions is estimated[1] to have been about 10 km across, and to have released some 10^8 Mtons of energy. This is 10,000 times the size of present nuclear arsenals, and one million times the size of the largest individual weapons. Clearly we must also be concerned about collisions with much more modest bodies, collisions which turn out to be much more probable. A "small" rock of 200 m diameter would typically release 1 Gton of energy upon hitting the Earth. Needless to say, anyone hapless enough to be near the collision site would die. This is not, however, the extent of the problem or of the death toll. Such a large concentrated explosion will loft great amounts of particulate matter into the stratosphere, and thereby cause global cooling for a period of one to two years. The resultant crop failures will lead to the deaths of many additional people. While such a "small" strike would not cause global extinction, it is a threat which we can and should protect against.

The two types of objects with which we must contend are asteroids and comets. Asteroids are dense rock or metal bodies located in nearby orbits, and will collide with the Earth at velocities up to 30–40 $km\,sec^{-1}$. Comets are low density balls of ice and gravel, which approach the Earth on essentially parabolic orbits. Hence, they can hit with speeds up to 72 $km\,sec^{-1}$, and present a less predictable, although lower probability threat.

There are estimated[2] to be some 400,000 asteroids of 1 km size, and 100 million ones with 100 m diameters. Fortunately, the vast number of these are in orbits which pose no threat to the Earth. The dangerous breed, the Apollo class, have orbits which cross that of the Earth, allowing them to collide with us. The number of these threatening asteroids is about 800 one km bodies, and 200,000 one hundred meter ones. The collision probabilities can be calculated[3], and predict a mean time between strikes of about 250,000 years for the larger asteroids, but only 1000 years for the 100 m sized ones. Hence the risk of a 100 Mton collision in a human lifetime is not large, but well worth insuring against.

To defend against an asteroid, you have to first realize that it is going to hit. Because they have closed orbits, which are stable over human timescales, one can map the asteroids, predicting which specific ones are threatening, and when. One can then leisurely implement a defense against the dangerous ones. At present, we have mapped only about 30 of the Apollo asteroids, most of which are larger than 1 km. Not surprisingly, none of these are dangerous. The presently known asteroids have been found optically, using telescopes to detect reflected sunlight. The majority have been found accidently, by a telescope looking for something else. A serious Apollo mapping operation would obviously employ dedicated telescopes and personnel. Predictions[4] based on a 48 inch Schmidt telescope being utilized 10 nights per month are that 25 Apollo asteroids per year would be found. Such a facility would be inexpensive, $< 1M\$yr^{-1}$, but lacks the throughput to catalog the expected asteroid inventory in a reasonable amount of time. One would like at least two orders of magnitude more capability, which can be attained with multiple automated telescopes: either about 100 on the ground, or about 10 in orbit. This system will quickly catalog all of the km-sized asteroids. From then on, it will have 3 tasks: to occasionally reexamine known asteroids, updating their orbits to account for planetary perturbations; to keep a watch out for asteroids and comets which are first-pass deadly; and to push the size threshold of cataloged asteroids down to and below the 100 m level.

Comets present a different type of threat than asteroids. The majority of comets which have been detected are new. That is, they are on orbits which are basically parabolas. Such objects cannot be pre-mapped, and hence must be continually searched for. Fortunately, new comets are bright and more easily detected than asteroids. The smaller flux of old comets which have been trapped into elliptical orbits can be found and cataloged in the same fashion as the asteroids. The new comets originate in the Oort Cloud, about which very little is known. It apparently[5] extends from 20,000 to 100,000 AU away from the Sun, and contains 10^{11} to 10^{13} comets. As with asteroids, the vast majority of these are no threat to us. Occasionally however, a passing star stirs up the cloud, causing some of the comets to fall inwards. They arrive in the inner Solar System a million years later, and either hit us or not. The collision probability is only 1-10% of that due to asteroids, but the mean impact speed is just over 50 $km\,sec^{-1}$, as opposed to about 25 $km\,sec^{-1}$ for asteroids. The unpredictability of comet strikes is in stark contrast to the asteroid threat, where one will be able to predict threatening rocks, and set thresholds for the size of surprise events.

Once an object is known to be on a collision path with the Earth, one must prevent the impact. The obvious solution, dodging, is precluded due to the cumbersome nature of the Earth. It is easier, and sufficient, to force the intruder to dodge. With most asteroids, the collision will be no surprise, and anticipated many years before the event. Because of this, and the fact that asteroid orbits are prograde with moderate inclinations, we can readily rendezvous with the rock, landing equipment on it. This machinery can then be used to slightly alter the asteroid's orbit, and remove the danger. Numerous proposals, for example[6], have been made to do just this for mining purposes. Here, one typically lands a magnetic gun on the asteroid, and expels a small fraction of the rock as reaction mass, steering the bulk of the asteroid into a more convenient orbit. Obviously, the same technology can be used to cause a colliding asteroid to miss the Earth. This task of defending against cataloged asteroids is not at all challenging, due to the long timelines permitted, and our easy access to the offending body; we can readily prevent even the 10 km sized, extinction-causing asteroids from impacting.

The more challenging threat is that posed by first-pass-deadly objects. Here one is facing a random and uncataloged danger. This clearly places a premium on a continual and vigorous lookout, in order to see the approaching threat as soon as possible. The range at which an incoming body can be detected depends on its albedo, size, and orbit. Small asteroids and comets, i.e., 100 Mton-equivalent threats, can be depressingly hard to see with currently designed hardware. For example, a computerized system was described in[7], employing a 1.8 meter aperture and performing an electronic blink test to detect moving objects at a magnitude of 19.4. Consider how this performs on "typical" small asteroids and comet. For a reference asteroid, postulate an orbit with a 2 year period, a 0.6 eccentricity, an inclination of 10°, and an albedo of 0.16. Let the baseline comet have a 0.5 AU periapse, a 90° inclination, and an albedo of 0.43. The asteroid would be seen at a range of 24 million km, giving a warning of just over 2 weeks. If the comet has time to develop a coma and tail, it will be considerably easier to see, giving us about 3 months warning. However, if the coma is slow to develop and we are forced to spot the nucleus, then typical reaction times are again 2 weeks, although detection occurs at a range of about 60 million km. In order to gain more time to respond, it will be necessary to use larger aperture telescopes. The gain in time with telescope aperture is less than linear, with a 7.2 meter telescope giving us 6 weeks warning for both the asteroid and the tailless comet.

Let us suppose that our ceaseless scrutiny of space has paid off, and we are warned of a previously unknown body approaching the Earth on a collision course. What can we do to prevent a deadly impact? Our task is challenging both due to the lack of time, and because the intruder is approaching us at speeds, typically 20-50 $km\,sec^{-1}$, which are considerably greater than we can attain with interceptor rockets. If we approach the projectile at much lower speeds than these, the engagement will occur close to the Earth, and hence require a larger angular deflection. Multistage rockets will be able to timely deliver a small fractional payload to the invader, but not to match velocities and land equipment on it. Our payload must deal with the projectile either on impact or during a flyby.

Therefore the most appropriate package to send is a nuclear bomb, as it provides a very compact and fast-acting way to deliver energy to our target. The warhead can be used either to fragment and disperse the object, or to deflect it en masse from its collision course with the Earth. Impact energies of 100 Mtons imply a comet mass of 300 kton, or an asteroid mass of 2 Mton. If its energy could be fully utilized, the bomb yields needed to vaporize these would be, respectively, 150 kT and 450 kT. These values are modest, but unfortunately both objects are thick and will not be uniformly energy-loaded by the explosive. Even a much larger warhead will only shatter them, leaving a spreading cloud of chunks. This dispersal is probably sufficient to deal with comets, since they are fragile and can be expected to split into many low ρr fragments, none of which will survive transit through the Earth's atmosphere. With asteroids, we prefer that they miss the planet entirely, either as shattered debris, or as a solid body.

The required deflection speed depends upon how early it is applied. If, for our 6 week warning example, we leave orbit with a 10 $km\,sec^{-1}$ interceptor, then we reach the rock 2.5 weeks before impact; a 5 $m\,sec^{-1}$ deflection is thus sufficient. An impact detonation used to shatter the asteroid may well give all the pieces this large a velocity; but the process is not very predictable. We could be more confident of success if the asteroid remained intact while being given an adequate shove sideways. Pushing an asteroid with a bomb is done by using the nuclear energy to heat and expel a fraction of the asteroidal mass; the reaction force then shoves the main body in the opposite direction.

The most straightforward coupling scheme is to use a surface burst, transporting energy into the asteroid by a shock wave. This will excavate a crater on the asteroid, with the crater ejecta acting as rocket exhaust. Project Icarus[8] at MIT used this approach in their proposal for deflecting the 1 km sized asteroid Icarus from a hypothetical Earth impact. It is difficult to predict the impulse which a given sized bomb will deliver to our asteroid; the results are very sensitive to the composition of the asteroid, and to the precise burst height of the bomb above the asteroid's surface. In order to develop an estimate, let's assume a moderate strength rock structure, and an impact detonation. This implies a cratering efficiency of about 2.8 tons of rock per ton of explosive yield.[9] Assume that 60% of this mass is ejected[10], and carries with it one half of the energy which was coupled into the rock, which is itself about 8% of the bomb yield.[11] We can then calculate an impulse of

$$I = 7.5 \times 10^{16} W \qquad gm\, cm\, sec^{-1}$$

where W is the device yield in megatons. This should be further reduced to account for angular[12], and velocity[10] variation in the ejecta; I will use a correction factor of 0.6. The device needed to deflect our typical 100 meter asteroid is found to have a yield of about 20 kT. While this is a very low value, an explosion of even this magnitude will probably shatter the asteroid, since the crater radius is about 40% that of the asteroid. Since this conclusion—that impulse delivery by cratering is energy-efficient but will shatter the asteroid into many fragments still able to penetrate the atmosphere—would be even more valid for weaker asteroids, let's consider less direct coupling schemes.

In order to deliver a gentler push, we should distribute the impulse over a larger fraction of the projectile's area while expending less of its mass. Developing the same impulse with less blow-off requires a less efficient coupling mechanism, i.e., a lower ejecta mass-to-energy ratio. Accordingly, we will have to spend more energy; but we can afford to deliver far more than 20 kT. The natural way to increase our areal coverage is to detonate the bomb at some distance above the asteroid. This, as it turns out, will automatically lead to lower values of the ejecta coupling efficiency. Indeed, standard coupling mechanisms, such as occur when bomb x-rays or plasma debris hit the asteroid's surface, will lead to very low efficiencies. Neutron coupling provides an attractive compromise between these values and that from impact detonation. Neutrons from the bomb heat and blow off an amount of material whose areal extent is set by the burst height, and whose depth is governed by the penetration scale of neutrons. A simple model in which local impulse varies as the square root of incident energy fluence and which has a cosine dependent neutron penetration depth, predicts an optimum burst height of one half the asteroidal radius. Using this geometry and more accurate blow-off calculations from hydro codes, one calculates that a 1 Mton bomb is required. The fraction of this which is neutron-coupled into the asteroid's surface is 4%, by coincidence the same fractional usage as for the impact case. The required increase in bomb yield is directly attributable to the difference in ejecta coupling efficiency, and shows up as a decrease in blow-off mass. The impact detonation expended over 3% of the asteroidal mass, while neutron coupling blows-off 0.07%, covering an area of 5800 m^2 to an average depth of 3 inches. The latter process is obviously much less likely to shatter the body. Furthermore, if the material is very weak and does fall apart, the broadly distributed impulse gives more confidence that all of the debris will have the required deflection velocity.

Cosmic bombardment kills; in the past, individuals, species, even entire branches of the evolutionary tree have been terminated by it. Unlike our predecessors, we have the ability to protect ourselves from this danger. To do this, we need a two-part system, featuring passive surveillance to identify threats, followed by an active defense to deflect or destroy incoming projectiles. We should first build a set of automated telescopes, using them to warn us of first-pass deadly comets and asteroids. As this surveillance continues, we will develop a catalog of the Apollo asteroids, enabling us to predict collisions with ever smaller asteroids many years in advance. Such anticipated threats can be dealt with leisurely; with neutron-rich bombs, such as presently exist, or with magnetic guns, which need not be developed until the requirement arises. Comets and small asteroids will not give us much warning; when the alarm sounds there will be no time for dithering. Hence, we should position a small number of interceptor rockets in Earth orbit; their warheads can be kept on the ground and delivered to them as needed. These interceptors will destroy comets by impact detonation, and deflect small asteroids by neutron ablation.

The human race should take out a cosmic collision insurance policy; the premiums are small and the benefits enormous.

References

1. L.W. Alvarez, W. Alvarez, F. Asaro, H.V. Michel, *Extraterrestrial Cause for the Cretaceous–Tertiary Extinction*, Science V208, 1095 (1980).
2. G.W. Wetherill, *Apollo Objects*, Scientific American V240, 54 (March 1979).
3. E.M. Shoemaker, *Astronomically Observable Crater-Forming Projectiles*, Impact and Explosion Cratering, Pergamon Press (1977), p 617.
4. M.J. Gaffey, E.F. Helin, B O'Leary, *An Assessment of Near-Earth Asteroid Resources*, NASA SP-428 (1979), p 191.
5. B. Lago, A. Cazenave, *Evolution of Cometary Perihelion Distances in Oort Cloud: Another Statistical Approach*, Icarus V53, 68 (1983).
6. B. O'Leary, *Mining the Apollo and Amor Asteroids*, Science V197, 363 (1977).
7. T. Gehrels, *Faint Comet Searching*, Icarus V47, 518 (1981).
8. Project Icarus, M.I.T. Press (1968).
9. H.F. Cooper, Jr., *Estimates of Crater Dimensions for Near-Surface Explosions of Nuclear and High-Explosive Sources*, Lawrence Livermore National Laboratory Report UCRL 13875, (1976).
10. W.R. Seebaugh, *A Dynamic Crater Ejecta Model*, Impact and Explosion Cratering, Pergamon Press (1977), p 1045.
11. C.P. Knowles, H.L. Brode, *The Theory of Cratering Phenomena, An Overview*, Impact and Explosion Cratering, Pergamon Press (1977), p 869.
12. H.F. Cooper, Jr., *A Summary of Explosion Cratering Phenomena Relevant to Meteor Impact Events*, Impact and Explosion Cratering, Pergamon Press (1977), p 11.